Searching for B_c mesons in the ATLAS experiment at LHC[*]

M. Galdón^a, R. Pérez Ochoa^{b,c} , M. A. Sanchis-Lozano^{a,b†} and J.A. Valls^{b,c}

(a) Departamento de Física Teórica

(b) Instituto de Física Corpuscular (IFIC)

(c) Departamento de Física Atómica, Molecular y Nuclear

Dr. Moliner 50, E-46100 Burjassot, Valencia (Spain)

We discuss the feasibility of the observation of the signal from B_c mesons in the ATLAS experiment at the LHC. In particular, we address the decay mode $B_c \to J/\psi\pi$ followed by the leptonic decay $J/\psi \to \mu^+\mu^-$, which should permit an accurate measurement of the B_c mass. We performed a Monte Carlo study of the signal and background concluding that a precision of ≈ 1 MeV for the B_c mass could be achieved after one year of running at "low" luminosity. The semileptonic decay $B_c \to J/\psi \ \mu^+\nu_\mu$ is also considered for a possible extraction of $|V_{cb}|$.

1. Introduction

There is a general consensus in the scientific community [1] that the scope of a future high-luminosity, high-energy hadron collider like LHC should not be restricted to the hunting of the standard model Higgs and its extensions, or the search for supersymmetry. Other topics requiring lower luminosities like top and beauty physics deserve in their own right a close attention.

In particular, a lot of work has been recently devoted to the observation of the B_c meson regarding both the hadroproduction [2] and decay [3] [4] (see references therein). Specifically, we shall focus on the feasibility of its detection in the ATLAS experiment at the LHC through some decay modes.

2. B_c signal

At the center-of-mass energy $\sqrt{s} = 14$ TeV, the cross-section for beauty production is assumed to be 500 μb leading to 5×10^{12} $b\bar{b}$ pairs per year-run (10^7 s) at a luminosity of $\mathcal{L} \approx 10^{33}$ cm^{-2} s^{-1}, corresponding to an integrated luminosity of ~ 10 fb^{-1}. The number of bottom pairs reduces, however, to 2.3×10^{10} by requiring events with a triggering muon coming from either a b or a $\bar{b}$ under the kinematic cuts $p_\perp > 6$ GeV/c and $|\eta| < 2.2$ [5].

On the other hand, assuming that the b-quark fragmentation yields a B_c or a B_c^* with probability of the order of 10^{-3} [2], the yield of B_c mesons (not yet triggered) per year of running would be roughly $\simeq 10^{10}$.

$B_c \to J/\psi \ \pi$ channel

This exclusive channel followed by the leptonic decay of the J/ψ resonance into a pair of oppositely charged muons offers several important ad-

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vantages. First of all, it allows for the mass reconstruction of the B_c meson. Observe also that anyone of the two muons can trigger the decay. Besides, it is very clean topologically with a common secondary vertex for all three charged particles, two of them (the muons) with the additional constraint of their invariant mass compatible with a J/ψ. Furthermore, the expected branching fraction is not too small, about 0.2% [6], which combined with the branching fraction of the leptonic decay of the resonance $BR(J/\psi \to \mu^+\mu^-) \simeq 6\%$ [7], yields an overall branching fraction for the signal of 10^{-4}. Thus, the number of such events turns out to be $\simeq 10^6$ per year of running.

A study has been performed in order to estimate the signal detection efficiency and background for the $B_c \to J/\psi(\to \mu^+\mu^-) \pi$ channel. The Monte Carlo employed for the signal simulation corresponds to a sample of $B_c \to J/\psi\pi$ events while for the background we have used a sample of inclusive b muon decays generated in all the cases with PYTHIA 5.7 .

Two types of background were considered: [3]

a) Combinatorial background due to muons from semileptonic decays of $b\bar{b}$ pairs produced at the main interaction. Cascade contributions such as $b\to c\to\mu$ are included as well for random combinations with any other muon in the same event.

b) Contamination from prompt J/ψ's in combination with another charged hadron (interpreted as a pion) from the main vertex. (In fact data released by Tevatron on the J/ψ yield point out a production rate quite larger than initially expected [9].) Incorrect tracking may give rise to the reconstruction of a (fake) secondary vertex, becoming a potential source of a large amount of background.

In a first step, we imposed the following cuts on events based on kinematic constraints:

- $p_{\perp min}(trig.\mu) = 6$ GeV/c ; $\mid \eta_{max}(trig.\mu) \mid = 2.2$

- $p_{\perp min}(\mu) = 3$ GeV/c ; $\mid \eta_{max}(\mu) \mid = 2.5$

- $p_{\perp min}(\pi) = 1$ GeV/c ; $\mid \eta_{max}(\pi) \mid = 2.5$

- $M_{\mu^+\mu^-} = M_{J/\psi} \pm 50$ MeV

The two first cuts correspond to the requirement of the 1st-level B physics trigger leading in our case to an efficiency of $\sim 15\%$ in triggering one of the two muons from the J/ψ. We next take into account the detection efficiency for the signal after applying the rest of $p_\perp$ and η cuts which turns out to be $\sim 21\%$. Setting the efficiency for muon identification as 80% and the track reconstruction as 95% [5] we get a combined detection efficiency of $\sim 2\%$ leading to an observable signal of about $20,000$ events per year of running.

The last of the cuts described above constrains the two muons invariant mass to be compatible (within two standard deviations [5]) with the nominal J/ψ mass, thus drastically reducing random combinations. However, background of class b) can potentially pass all the kinematic cuts by a large amount, so another type of rejection is required.

To this end, we adapted to our needs the vertex reconstruction (i.e. vertex finding and fitting) routines of the LEP experiment DELPHI at CERN [10]. The vertex fitting algorithm provides as output the coordinates of the secondary vertex, the track momenta re-evaluated with the vertex constraint and the goodness of the fit by means of the total χ^2 as well as the contribution of each single track to it. In particular, we employed for background rejection the three spatial coordinates and the χ^2 for each fitted secondary vertex formed by the two muons and the charged hadron (assumed to be a pion) satisfying the above kinematic constraints. The distance between the reconstructed vertex and the primary (pp) interaction point was thereby determined. We shall refer to it as the decay length even for background events of class b).

Hence, candidate (either signal or background)

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[3]Muons coming from semileptonic decays of long-lived particles such as pions or kaons contribute in a negligible amount to trigger rates. On the other hand B decays into J/ψ and a charged particle would give an invariant mass quite below the B_c mass so they are of no concern

events were required to pass the following extra cuts:

- total $\chi^2 < \chi_0^2$

- $\chi_i^2 < \frac{\chi_0^2}{3}$ for each single track-i

- decay length larger than L_0

where χ_0^2, L_0 have to be optimized to remove the background as much as possible but with a good acceptance for the signal. In our analysis we found $\chi_0^2 = 8$ and $L_0 = 350 \ \mu m$.

Figure 1 shows the reconstructed $(\mu^+\mu^-)_{J/\psi} \ \pi$ mass distribution for the expected signal above the surviving background once all the cuts have been applied, for an integrated luminosity of 10 fb^{-1} [3].

In summary, we have found that the self-triggering weak decay $B_c \rightarrow J/\psi \ \pi$, followed by the leptonic decay of the J/ψ into two muons, could be clearly observed in the ATLAS detector at LHC. Under rather conservative assumptions, a total number of $\approx 10,000$ signal events could be fully reconstructed after one year run, corresponding to 10 fb^{-1} at "low" luminosity ($\approx 10^{33}$ cm^{-2} s^{-1}). This represents a signal to background ratio of about 0.5 with a statistical significance of ≈ 20 standard deviations above a nearby almost flat background. The foreseen mass resolution (standard deviation) of the B_c meson is about 40 MeV representing a precision of about 1 MeV for the mass measurement.

$B_c \rightarrow J/\psi \ \mu^+ \ \nu_\mu$ channel

In spite of the fact that this channel does not permit the measurement of the B_c mass, its signature would be quite clean experimentally when the J/ψ decays into a pair of muons, providing a three muon vertex. In the following we shall argue that in LHC experiments this decay mode could provide a reliable extraction of the mixing matrix element $|V_{cb}|$.

The expected semileptonic branching ratio $\simeq 2\%$ [6] together with the leptonic branching ratio for the J/ψ into two muons $\simeq 6\%$ [7], yields an overall branching fraction of order 10^{-3}. We
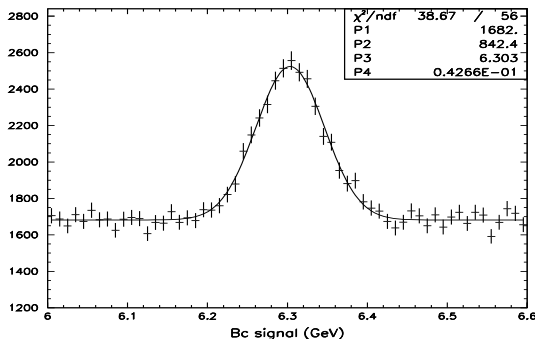

Figure 1. Reconstructed $(\mu^+\mu^-)_{J/\psi} \ \pi$ mass distribution after cuts. The nominal value for the B_c mass was set equal to 6.3 GeV. The solid line corresponds to a linear+Gaussian fit

next combine the last BF with the acceptance of the muon trigger $\simeq 15\%$ (where the three possible triggering muons per decay have been taken into account.) Besides, the detection of the two remaining particles (i.e. the non-triggering muons satisfying some $p_\perp$ and η cuts [8]) amounts to an acceptance for signal events of $\simeq 12\%$. Finally, we assume an identification efficiency for each muon of 0.8 [5] yielding a combined value of $0.8^3 \simeq 0.5$.

Thereby, the expected number of useful B_c decays [4] could reach several 10^5 per year at low luminosity.

Such large statistics together with the foreseen precision in the muon momentum measurement [5] should permit the experimental access to the kinematic region near zero-recoil of charmonium (with respect to the B_c meson) with a good energy/momentum resolution. Moreover, very stringent cuts can be put on events and hence, expectedly, background could be almost entirely removed from the event sample permitting a very

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[4]Semi-electronic $B_c \rightarrow J/\psi e^+ \nu$ decays, followed by the J/ψ decay into $\mu^+\mu^-$ can be considered as well. In addition, if the muon from the semi-muonic decay (1) gives the trigger, the event can be selected with the mode $J/\psi \rightarrow e^+e^-$. The trigger acceptance for the former is $\simeq 12\%$ whereas for the latter is $\simeq 3\%$ [8]

precise determination of the B_c lifetime. We explore all these issues in the following section.

Theory inputs and determination of $|V_{cb}|$

Next we examine in detail the possibility of extracting $|V_{cb}|$ from experimental data. Let us start by recalling that

$$
\frac{d\Gamma(B_c \to J/\psi\ \mu^+\nu)}{dw} =
$$
$$
\frac{1}{\tau}\frac{dBr(B_c \to J/\psi\ \mu^+\nu)}{dw} \tag{1}
$$

The differential branching ratio dBr/dw can be written as

$$
\frac{dBr(B_c \to J/\psi\ \mu^+\nu)}{dw} =
$$
$$
\frac{1}{N(B_c)}\frac{dN(B_c \to J/\psi\ \mu^+\nu)}{dw} \tag{2}
$$

where dN/dw represents the number of semileptonic decays per unit of w for a certain integrated luminosity, once corrected by detection efficiency; $N(B_c)$ is the corresponding total yield of B_c's produced for such integrated luminosity. (Notice that τ could be determined accurately from the same collected sample of semileptonic B_c decays.)

In order to get $N(B_c)$ it will be convenient to compare the B_c production rate to the prompt ψ' yield in pp collisions, for the same integrated luminosity. Therefore

$$
N(B_c) = \frac{\sigma(pp \to B_c + X)}{\sigma(pp \to \psi' + X)}
$$
$$
\times \frac{N(\psi' \to \mu^+\mu^-)}{\epsilon_{\psi'}\cdot BF(\psi' \to \mu^+\mu^-)} \tag{3}
$$

where $N(\psi' \to \mu^+\mu^-)$ stands for the number of prompt ψ' to be experimentally detected through the muonic decay mode and $\epsilon_{\psi'}$ denotes its detection efficiency. Contamination from weak decays of B mesons into ψ' states should be efficiently removed by means of the vertex capability of the inner detector.

Therefore, we suggest normalizing the B_c sample with the aid of the ψ' yield through expression (3). The ψ' state is probably preferable to the J/ψ mainly because the former expectedly should not be fed down by higher charmonium states [5]. Instead, data released by Tevatron shows that the J/ψ indirect production through χ_c intermediate states may be also important. Let us also remark that the production of the ψ' resonance in $p\overline{p}$ collisions is more than one order of magnitude larger than initially expected [13] [9].

At sufficiently large $p_\perp$ [6], one reasonably expects that the main contribution to heavy quarkonia production comes from the splitting of a heavy quark or a gluon. Indeed, even though the fragmentation process is of higher order in α_s than the "conventional" leading order diagrams [14], the former is enhanced by powers of $p_\perp/m_Q$ relative to the latter [2] [15]. Although the situation is still controversial in the literature, there are strong indications from very detailed calculations (see [16] [17] and references therein) that fragmentation indeed dominates for large enough $p_\perp$. In the following, we first examine some color-singlet mechanisms, expected to contribute largely to the high-$p_\perp$ inclusive production of prompt heavy quarkonia.

On the other hand, according to the set of papers in [2], perturbative QCD can provide a reliable calculation for the fragmentation function of a high-$p_\perp$ parton into B_c states with only few input parameters: the QCD running constant α_s, the charm and bottom masses, and the square of the radial wave function at the origin $|R(0)|^2$. Note that the largest uncertainty for normalization purposes comes from the (third power of the) charm mass in the fragmentation function (see [2] for explicit expressions). However, we are only interested in the ratio

$$
r = \frac{\sigma(pp \to B_c + X)}{\sigma(pp \to \psi' + X)} \tag{4}
$$

[5]See Ref. [12] for an alternative explanation of the observed ψ' surplus found in Tevatron. However this mechanism would require an uncomfortable large radiative BF for higher resonances

[6]We find an average $p_\perp \approx 20$ GeV/c for B_c mesons simply passing the kinematics cuts on $p_\perp$ and $|\eta|$ of the decay muons [8]

where each cross section can be written as a convolution of the parton distribution functions of the colliding protons, the cross section for the hard subprocess leading to the fragmenting gluon or heavy quark and the respective fragmentation function [2]. Thus notice that the fragmentation functions $D_{\bar{b}\to B_c}$, $D_{g\to B_c}$ and $D_{c\to\psi'}$, $D_{g\to\psi'}$ [18], which themselves are independent of the parton-level subprocesses, appear combined as a ratio. Therefore, those uncertainties coming from the common overall factor m_c^3 automatically cancel each other. Moreover, those uncertainties introduced by the parton distribution functions also should significantly diminish in r as well. Still one must evaluate the ratio

$$\frac{|R_{B_c}(0)|^2}{|R_{\psi'}(0)|^2} \tag{5}$$

In fact there is the possibility of expressing the above ratio (aside trivial factors) according to the general factorization analysis of [19] in a more rigorous way as

$$\kappa_0 = \frac{<0|O_1^{B_c}(^1S_0)|0>}{<0|O_1^{\psi'}(^3S_1)|0>} \tag{6}$$

where O_n^X are local four fermion operators[7] and the matrix elements can be evaluated from NRQCD. A similar expression holds for the B_c^*. (Moreover, the denominator can be determined from the measured leptonic width of the ψ'.)

Recently, an additional color-octet fragmentation mechanism [20] has been suggested in order to reconcile the experimental results on inclusive ψ' production with theoretical predictions. This mechanism assumes the creation from gluon fragmentation of a $c\bar{c}$ pair in a color-octet state, in analogy to χ_c production [13]. Then a new nonperturbative parameter $H'_{8(\psi')}$ is required, appearing in r combined as the dimensionless factor

$$\kappa_{8(\psi')} = \frac{<0|O_8^{\psi'}(^3S_1)|0>}{<0|O_1^{\psi'}(^3S_1)|0>} \approx \frac{2\pi m_c^2 H'_{8(\psi')}}{|R_{\psi'}(0)|^2} \tag{7}$$

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[7]This implies the application of NRQCD to the evaluation of the non-perturvative part of the fragmentation function of a b quark into a $b\bar{c}$ bound state. Therefore four quark operators involve both b- and c-quark fields in this case[25].

where we remark that it can be computed in terms of NRQCD matrix elements [19] [8].

Furthermore, if we do not neglect the contribution to the total B_c production of those orbital excitations like P-wave states, new fragmentation functions $D_{\bar{b}\to\bar{b}c(P)}$ come into play [23]. Accordingly, some new κ_i factors will appear which can be conveniently expressed, for instance in analogy to Eqs. (6) and (7), as:

$$\begin{aligned} \kappa_{1(B_c)} &= \frac{1}{\hat{m}^2}\frac{<0|O_1^{B_c}(P_J)|0>}{<0|O_1^{B_c}(^1S_0)|0>} \\ &\propto \frac{8\pi\hat{m}^2 H_{1(\bar{b}c)}}{|R_{B_c}(0)|^2} \end{aligned} \tag{8}$$

and

$$\begin{aligned} \kappa_{8(B_c)} &= \frac{1}{\hat{m}^2}\frac{<0|O_8^{B_c}(^3S_1)|0>}{<0|O_1^{B_c}(^1S_0)|0>} \\ &\propto \frac{8\pi\hat{m}^2 H'_{8(\bar{b}c)}}{|R_{B_c}(0)|^2} \end{aligned} \tag{9}$$

where $\hat{m}$ is the reduced mass of the b and c quarks. The long-distance H_1 parameter [22] is related to the square of the derivative of the color-singlet wave function at the origin.

Higher B_c resonances like D-wave states might be further taken into account, introducing new nonperturbative parameters involving higher derivatives of the wave function at the origin, or the NRQCD matrix element analogues.

In sum, the evaluation of such κ_i parameters would allow one to complete the computation of the ratio r and thereby to obtain from the experimental measurement of the ψ' yield, the total number of B_c events for an integrated luminosity with the aid of expression (3).

On the other hand, the hadronic transition $B_c\to J/\psi$ involves two heavy-heavy systems whereby heavy quark spin symmetry should be still valid as a first order approach [4] [25]. This

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[8]$H'_{8(\psi')}$ can be phenomenologically estimated from B or Υ decays as well [13] [21] [22]. On the other hand, according to a nonrelativistic quark model H'_8 is related to a fictitious color-octet wave function at the origin

permits the introduction of the analogue of the Isgur-Wise function for transitions involving doubly heavy hadrons, denoted by $\eta_{12}(v_1 \cdot v_2)$. At the non-recoil point $v_1 = v_2$, we shall write

$$< J/\psi| \, A^\mu \, |B_c > = 2 \, \eta_{12}(1) \, \sqrt{m_1 m_2} \, \varepsilon_2^{*\mu} \quad (10)$$

where $A^\mu = \overline{c}\gamma^\mu\gamma_5 b$ stands for the axial-vector current and ε_2^μ represents the four-vector polarization of the J/ψ.

Following similar steps as in the B decay into D^* [26], we write

$$\lim_{w\to 1} \frac{1}{\sqrt{w^2-1}} \, \frac{d\Gamma(B_c \to J/\psi \, \mu^+\nu)}{dw} =$$
$$\frac{G_F^2}{4\pi^3} \, (m_1 - m_2)^2 \, m_2^3 \, \eta_{12}^2(1) \, |V_{cb}|^2 \quad (11)$$

It is of key importance from the theoretical side in our proposal, the existence of a single form factor in the above expression to be determined theoretically in a rigorous manner. Note that $\eta_{12}(1)$ may be interpreted in first approximation as the overlap of the initial and final hadron wave functions [4] [24]. Moreover, due to the intrinsic non-relativistic nature of its heavy constituents, non-relativistic QCD on the lattice or even refined potential based models of hadrons, could be applied in order to get η_{12} and its slope at zero recoil in a reliable way.

This fact in conjunction with the presumed accuracy of the J/ψ momentum measurement suggests determining $|V_{cb}|$ in a similar way as in the method proposed by Neubert [27] through the $\overline{B} \to D^* \ell \overline{\nu}$ decay.

For the purpose of illustration, we have depicted in figure 2 some expected typical points and error bars for the decay $B_c \to J/\psi(\to\mu^+\mu^-) \, \mu^+\nu$ for a definite prediction of the ratio of production cross sections r in Eq.(4).

Under this condition, let us remark that the uncertainty on w (i.e the horizontal error bars) is of systematic nature, mainly coming from the B_c flight-path reconstruction. With regard to the vertical coordinate $\eta_{12}(w) \cdot |V_{cb}|$, we have assumed that its uncertainty is essentially statistical [3].
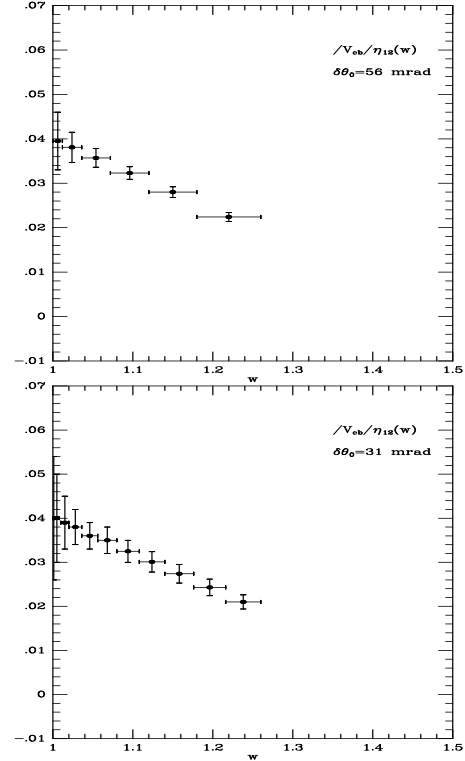

Figure 2. Hypothetical $\eta_{12}(w) \cdot |V_{cb}|$ distributions of the decay $B_c \to J/\psi\mu^+\nu$ for a 500 events sample tentatively assigned to an integrated luminosity of 20 fb^{-1} (i.e. two years of running at low luminosity). It was assumed an spatial resolution for the B_c flight-path reconstruction of $\sigma \approx 100$ μm and its lifetime is allowed to vary in the interval $\tau = 0.5 - 1$ ps. Horizontal bars show systematic errors basically limiting the number of experimental points. Vertical bars take into account the statistical fluctuations of the sampled events in the bin (distributed according to the expected differential rate for a pseudoscalar to vector semileptonic decay [26]). Points line up with η'_{12} set equal to -2. For more details see Ref. [28]

It is important to stress that the quantity to be experimentally measured with a large accuracy from $B_c \to J/\psi \, \mu^+ \nu$ decays can be written as the linear combination:

$$r^{1/2} \times \eta_{12}(1) \times |V_{cb}|$$

In summary, we suggest to keep an open mind on the possibility of an alternative determination of $|V_{cb}|$ from semileptonic decays of B_c mesons at LHC. Even if at the time LHC will start to run, B factories would have already provided a (still) more precise value of $|V_{cb}|$ than at present via the semileptonic B decay, an independent determination of it should bring a valuable cross-check. On the other hand, a lot of activity is being devoted to the analysis of inclusive production of prompt charmonium resonances at Fermilab. Therefore we conclude that if the fragmentation approach to describe the production of heavy quarkonia at the large transverse momentum domain is accurately tested (and tuned) from experimental data, B_c semileptonic decays could be competitive with the B ones.

Alternatively, one can turn the question round and consider $|V_{cb}|$ as a well-known parameter thus verifying QCD calculations, either at the production or at the weak decay level. Indeed, fragmentation into heavy quarkonia offers an interesting check of perturbative QCD and a deep insight into the nonperturbative dynamics in the hadronic formation. Besides, a precise knowledge of the B_c production rate is a necessary condition for the experimental measurement of the absolute branching fraction of any of its decay modes.

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